A tri-modal flocculation model coupled with TELEMAC for suspended cohesive sediments in the Belgian coastal zone

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Introduction

Estuarine and coastal regions are often characterized by a high variability of suspended sediment concentrations (SSC). The Belgian coastal zone is one of those areas where dredging works are conducted to maintain harbours and navigation channels (Fettweis et al., 2016). To investigate the SSC dynamics it is essential to understand the flocculation processes of estuarine mud, since it alters the sediment settling flux by aggregating individual clay particles into larger flocs. Previous curve fitting analysis of measured floc size distributions (FSDs) in the Belgium coastal zones showed that the multimodal FSDs can be decomposed into four log-normal FSDs to identify groups of primary particles, microflocs, macroflocs, and megaflocs, respectively (Lee et al., 2012). A two-class population balance model (PBM2C) was firstly developed using size-fixed class 1 particles (primary particles + microflocs) and size-varying class 2 particles (macroflocs + megaflocs) to describe the aggregation and breakage process of cohesive sediments. This simple model was validated by settling column test (Lee et al., 2011) and some field data collected in Zeebrugge (Lee et al., 2014), and later was coupled in the open source TELEMAC system and validated by using the same data set (Ernst, 2016). However, this two class assumption may be oversimplified as it does not address the large megaflocs that form after the peak of algae bloom periods. Moreover, the maximum errors for estimating the settling flux may largely decrease by tracking three size classes instead of two (Lee et al., 2012). For these reasons, a three-class population balance model (PBM3C) was developed in this study, also coupled with the open source TELEMAC modelling suite for the hydrodynamic and turbulence sections, to simulate the characteristic sizes of three size classes, i.e., microflocs (including primary particles), macroflocs, and megaflocs, respectively. A more recent data set from the WZBuoy in the Belgian coastal zone is used to validate the newly developed PBM3C. The objective of this study is to develop the PBM3C and implement it in TELEMAC to mimic flocculation processes of cohesive sediments, especially to reasonably address the population of megaflocs that previous PBM2C simply ignored.

Numerical modelling

Hydrodynamic model

The general open source software TELEMAC developed by the LNHE (Laboratoire National d'Hydraulique et Environnement) of EDF (Electricité De France) is used to solve the Navier-Stokes equations for variable water depth and velocity components, and to solve the tracer transport equation for various active and passive tracers. The transport of tracers is of major importance in the implementation of a flocculation model in TELEMAC3D.

Flocculation model

The PBM3C is developed to describe the flocculation processes, as an improvement of the previous PBM2C. As shown in Fig. 1, a system of equations are set up to track (1) the number of microflocs, macroflocs and megaflocs per unit volume, with symbol N_P, N_{F1}, and N_{F2}, respectively, (2) the total number of microflocs in all macroflocs (but not in megaflocs) per unit volume N_{T1}, and (3) the total number of microflocs in all megaflocs (but not in macroflocs) per unit volume N_{T2}. Take a one-dimensional vertical case as an example, the governing equation can be written as:

$$\frac{\partial N_i}{\partial t} + (w - \omega_{s,i})\frac{\partial N_i}{\partial z} = \frac{\partial}{\partial z}\left(\nu_t \frac{\partial N_i}{\partial z}\right) + (A_i + B_i) \qquad i = P, F1, F2, T1, T2 \qquad (1)$$

where N_i is number concentration (in unit of m^{-3}), w is the vertical velocity of fluid, ω_s is the settling velocity, and ν_t is the eddy viscosity. A_i & B_i are source and sink terms, which include (1) the aggregation of two microflocs, or two macroflocs, or two megaflocs, (2) the aggregation of a microfloc and a macrofloc, or a microfloc and a megafloc, or a macrofloc and a megafloc, and (3) the breakage of a macrofloc, or a megafloc. The average number of microflocs in one macrofloc per unit volume is $N_{C1} = N_{T1} / N_{F1}$, and the average number of microflocs in one megafloc per unit volume is $N_{C2} = N_{T2} / N_{F2}$. Thus, the sizes of macroflocs and megaflocs can be determined as $D_{Fi} =$

$D_P N_{Ci}^{1/nf}$ (i = 1, 2), where D_P, D_{F1}, and D_{F2} are the characteristic sizes of microflocs, macroflocs, and megaflocs, respectively, and nf is the fractal dimension. The five parameters, i.e., N_P, N_{F1}, N_{F2}, N_{T1}, and N_{T2}, are defined as tracers in TELEMAC as long as flocculation is toggled on (e.g., a predefined logical variable PBM3C is set to true). This PBM3C flocculation model can be included in the TELEMAC software with appropriate modification of the subroutines VITCHU, WCHIND, CLSEDI, SOULSBYFLOC3D, FONVAS, etc. in TELEMAC.

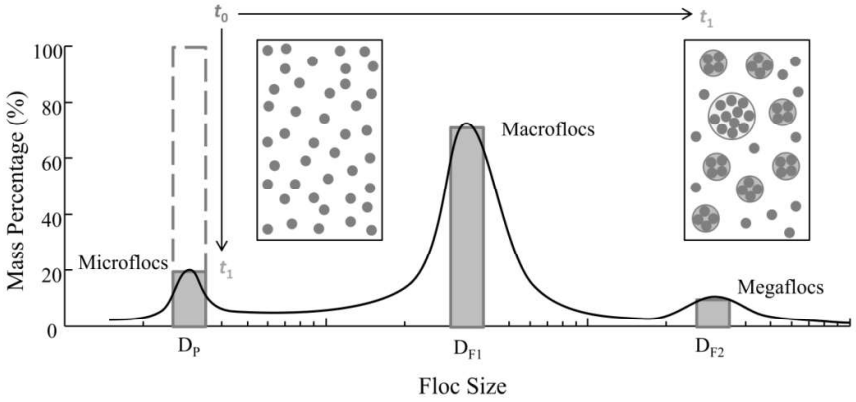

Fig. 1. Conceptual diagram for three-class population balance model (PBM3C).

Field measurements

The station WZBuoy is located about 2km outside the entrance of Zeebrugge harbour which is situated in the coastal turbidity maximum area along the southern North Sea near the Belgian coast (Fettweis et al., 2016). Although measurements were conducted with tripods for several years, only the data for several selected tidal cycles around Julian Day 322 in the year 2013 were used to validate the model. Velocity profiles and water surface elevation were recorded by an upward looking ADCP (Acoustic Doppler Current Profiler) which was mounted together with the tripod. The time series of FSDs were collected by the LISST (Laser In-Situ Scattering and Transmissometry), and temperature, salinity, and SSCs were measured or derived from the ADCP backscatter strength. Time series of water depth and the average temperature and salinity are treated as inputs to drive the model, while the velocity profiles, SSC profiles, and FSDs are used to validate the model outputs.

Results and conclusions

The PBM3C enabled TELEMAC software is validated by the flow, sediment and floc size distribution data from the WZBuoy station in the Belgian coastal zone within an intra-tidal time scale. More complicated processes such as the effect of biofilms and interaction with microplastic particles will be included in this system in a later stage.

Acknowledgements

This research was funded by the BelSPO (Belgian Science Policy Office) in the framework of the BRAIN-be (Belgian Research Action through Interdisciplinary Networks) INDI67 project, and by the JPI Oceans (Joint Programming Initiative Healthy and Productive Seas and Oceans) in the framework of the WEATHER-MIC (Microplastic Weathering) project.

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